# MAGNETOHYDRODYNAMIC ACCELERATOR WITH EQUILIBRIUM PLASMA

SUKARSAN

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## ABSTRACT

Magnetohydrodynamic (MHD) has been identified as one of the technologies that is capable of producing hypervelocity, high flight dynamic pressure and clean-air wind tunnel simulations for development of air-breathing propulsion systems. In this application, an MHD accelerator is used to accelerate the plasma flow at the exit of the combustor. The objective of this study is to investigate the performance of an MHD accelerator for space propulsion system using equilibrium air plasma as the working gas. The fundamental performance of MHD accelerator such as flow performance, electrical performance, and propulsion performance are described in this study. The performance of Faraday type has been evaluated at different levels of applied current density and magnetic field. For diagonal type, the performance has been evaluated at different levels of applied current, magnetic field, and constant diagonal angle. The MacCormack scheme is employed in order to solve the set of differential equations with MHD approximations. In order to represent the actual application of the MHD accelerator propulsion system, working gas of air-plasma composed of diatomic molecules of nitrogen and oxygen seeded with potassium is considered. The MHD Augmented Propulsion Experiment (MAPX) channel designed by the National Aeronautics and Space Administration (NASA) is used in this study. The best performance of diagonal MHD accelerator is obtained by setting the constant diagonal angle of $55^o$. The optimum current required for propulsion performance is 300 A for a magnetic field of 2 T and constant diagonal angle of $55^o$. In this condition, the value of the exit flow velocity, thrust and specific impulse are 3848 m/s, 363 N and 2736 s, respectively. The propulsion performance of the Faraday type is better than the diagonal type for an electrical power input of greater than 1100 kW. The optimum performance when increasing the applied current and magnetic field is dominated by **j x B** Lorentz force acceleration. On the other hand, increasing the applied current and magnetic field will increase the Joule heating and the **u x B** term's contribution which are detrimental to the propulsion performance. Moreover, the friction forces resist the flow performance, especially near the exit of the channel.

# ABSTRAK

Magnetohidrodinamik (MHD) telah dikenal pasti sebagai salah satu teknologi yang berupaya menghasilkan hiperhalaju, tekanan dinamik penerbangan tinggi dan simulasi terowong angin udara bersih untuk pembangunan sistem perejangan udara. Di dalam aplikasi ini, pemecut MHD digunakan untuk memecut aliran plasma di keluaran pembakar. Tujuan utama kajian ini adalah untuk menyiasat prestasi pemecut MHD untuk sistem perejangan angkasa menggunakan udara plasma yang seimbang. Prestasi asas pemecut MHD seperti prestasi aliran, prestasi elektrik dan prestasi perejangan digambarkan di dalam kajian ini. Prestasi jenis Faraday telah diuji dengan ketumpatan arus dan medan magnet yang berbeza. Untuk jenis pepenjuru, prestasi diuji dalam beberapa aras masukan arus elektrik, medan magnet dengan sudut pepenjuru yang tetap. Skim *MacCormack* digunakan untuk menyelesaikan beberapa persamaan pembezaan dengan penghampiran MHD. Bagi tujuan menggambarkan aplikasi sebenar sistem pemecut MHD, plasma udara mengandungi molekul dwiatom nitrogen dan oksigen dengan kalium telah diambilkan. Saluran Ujikaji Penambahan Perejangan MHD (MAPX) yang direkabentuk oleh Pentadbiran Aeronautik dan Angkasa Lepas Kebangsaan Amerika (NASA) digunakan dalam kajian ini. Prestasi terbaik pemecut MHD jenis pepenjuru diperolehi dengan menetapkan sudut pepenjuru tetap $55^{o}$. Arus elektrik optimal yang diperlukan untuk prestasi perejangan adalah 300 A untuk medan magnet daripada 2 T dan sudut pepenjuru tetap $55^{o}$. Dalam keadaan ini, nilai daripada halaju aliran keluar, tujahan dan impuls tertentu adalah masing-masing 3848 m/s, 363 N dan 2736 s. Prestasi perejangan jenis Faraday lebih dominan daripada jenis pepenjuru dalam kes input kuasa elektrik lebih besar daripada 1100 kW. Prestasi terbaik ketika diterapkan arus elektrik dan medan magnet didominasi oleh percepatan **j x B** daya Lorentz. Sementara di sisi lain peningkatan arus elektrik dan medan magnet akan meningkatkan pemanasan Joule dan sumbangan **u x B** yang merugikan prestasi perejangan. Selain itu, daya geseran melawan prestasi aliran, terutama di dekat pintu keluar saluran.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Up to the present time in the short history of space propulsion, almost all the space propulsion missions have been accomplished with chemical propulsion system. The big advantage of chemical propulsion is that it can provide very high thrust to weight ratio by allowing very high propellant mass flow rate. In chemical propulsion, the thermal energy produced by the chemical reaction of the propellant is converted to exhaust kinetic energy; the specific impulse is dependent upon the propellant selected. Unfortunately, conventional chemical space propulsion, whether liquid or solid, monopropellant or bipropellant, are fundamentally limited by their available combustion reaction energies and heat transfer tolerances to exhaust speeds of a few thousand meters per second, whereas many attractive space missions entail characteristic velocity increments at least an order of magnitude higher. Thus, some fundamentally different concept for the acceleration of propellant mass that circumvents the intrinsic limitation of chemical thermodynamic expansion is required [1].

Electrical propulsion (EP) is broadly defined as the acceleration of a working fluid for propulsion by electrical heating and /or by electric and magnetic body forces. In EP the energy required to produce the acceleration is obtained from an onboard electrical power source, solar arrays or beamed energy received from ground or in-space stations. The total available exhaust velocity, or the specific impulse, is limited only by the capacity and efficiency of the electrical supply, and is therefore de-coupled from the propellant. So, EP can achieve much higher specific impulse than chemical propulsion. Historically, conceptually, and pragmatically, EP has tended to subdivide into three categories: (i) Electrothermal propulsion, wherein the propellant is heated by some electrical process, then expanded through a suitable nozzle; (ii) Electrostatic propulsion, wherein the propellant is accelerated by direct application of electrostatic forces to ionized particles; (iii) Electromagnet propulsion, wherein the propellant is accelerated under the combined action of electric and magnetic fields [2].

This study focuses with the third category of EP, electromagnetic propulsion, especially Magnetohydrodynamic (MHD) accelerator. MHD acceleration has been identified as one technology that is capable of producing hypervelocity, high flight dynamic pressure, clean-air wind tunnel simulations for development of air-breathing propulsion systems. Additionally, an MHD accelerator may be used to accelerate plasma flow at the exit of the combustor for Scramjet engine augmentation [3], [4].

In an MHD accelerator, there are three basic design configurations (i.e. Faraday, Hall, and Diagonal type), and previous study on MHD accelerator performance with different electrode connections has been conducted [4] - [7]. These studies confirmed that the Faraday type configuration has the best acceleration efficiency and the Diagonal type configuration can approach similar levels of efficiency. In actual application as a propulsion system, segmented the Faraday configuration is very complicated, requires many independent power supplies, and leads to increased cost and weight [8]. Therefore, a diagonal configured accelerator offers improvements in power density, push power, and efficiency above that of the Hall accelerator without the added cost, complexity, and weight of the Faraday accelerator. Furthermore, it is most plausible for aerospace propulsion application systems [9], [10].

In aircraft applications, one of the most important parameters quantifying engine performance is thrust, T. If an engine does not generate enough thrust to overcome airframe drag, a given aircraft cannot fly. It is important to note that the resulting thrust has two contributions. One is due to the mass flux and flow acceleration. The second is from pressure differences between the engine exit and atmosphere [11]. In this study, the MHD accelerator for thrust augmentation in flight applications is investigated.

The acceleration forces of MHDs is mostly produced by Lorentz body forces (**j** x **B**) which are attained by interaction of the electric and magnetic fields [12]. The magnetic field is applied perpendicular to the gas flow so as to provide an accelerating force to the working gas. On the other hand, the **j** x **B** pushing force is essentially opposed by an induced $\mathbf{j_{ind}}$ x **B** force from the induced current density, $\mathbf{j_{ind}}$ that comes from the **u** x **B** term's contributions in the generalized Ohm's law. This implies that simply increasing the magnetic field in an MHD accelerator would not always be beneficial.

## 1.2 Aim of Research

### 1.2.1 Objectives of the Study

In this study, the performances of an MHD accelerator are studied with the following objectives:

(a) To study the performance of an MHD accelerator with equilibrium plasma.

(b) To compare and analyze the performance of Faraday and diagonal MHD accelerator.

(c) To compare and analyze the performance of an MHD accelerator at different applied current, magnetic field and setting of constant diagonal angle.

(d) To analyze the potential capability of MHD accelerators for space propulsion system.

### 1.2.2 Scope of the Study

This study is conducted using a one-dimensional numerical simulation. The numerical simulation has been developed based on a set of differential equations with MHD approximation. To solve this set of differential equations, the MacCormack scheme is used, which is one of the finite difference methods using an artificial viscosity under initial conditions of isentropic flow. A specified channel designed and developed at NASA Marshall Space Flight Center is used in the numerical simulation. In this study, equilibrium air plasma composed with diatomic molecules of nitrogen and oxygen seeded with potassium has been considered in order to represent the actual application of the MHD accelerator propulsion system.

## 1.3 Thesis Organizations

This thesis consists of five chapters.

Chapter 1 contains the overview of this study, aims of research such as objectives and scope of the study. Thesis organization covers a brief review on its content.

Chapter 2 compiles the basic theory of MHD acceleration. This chapter presents the basic theory of MHD which includes basic relation and several types of MHD connection.

Chapter 3 describes the numerical simulation procedures for analysis of MHD accelerator. This chapter presents the numerical procedures of simulation, one-dimensional MHD simulation, MacCormack method, MHD accelerator channel, characteristics of working gas and the propulsion performance parameter.

Chapter 4 describes the performance of the Faraday MHD accelerator based on the simulation results. Fundamental performance of the MHD accelerator such as flow performance, electrical performance, propulsion performance and electrical efficiency are explained in this chapter. The performances are evaluated at different levels of applied magnetic field and constant $j_y$ current density.

Chapter 5 describes the performance of the diagonal MHD accelerator based on the simulation results. In this chapter, the discussion on the performances of the diagonal MHD accelerator are based on the simulation results which consist of three different cases: varying the setting of constant diagonal angle from $40^o$ to $70^o$, varying the applied current from 50 A to 350 A (at 50 A interval) and varying the applied magnetic field from 0.5 T to 2 T (at 0.5 T interval).

Finally, Chapter 6 covers the overall conclusion and future recommendations for further studies. This chapter summarizes the result obtained throughout the study on the performance of Faraday and diagonal MHD accelerator. Recommendations are presented and discussed for further improvement of the study.

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